7. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 7-1). Landfills were the largest source of anthropogenic methane (CH_4) emissions, accounting for 33 percent of the U.S. total.[1] Smaller amounts of CH_4 are emitted from wastewater systems by bacteria used in various treatment processes. Wastewater treatment systems are also a potentially significant source of nitrous oxide (N_2O) emissions; however, methodologies are not currently available to develop a complete estimate. Nitrous oxide emissions from the treatment of the human sewage component of wastewater were estimated, however, using a simplified methodology. Nitrogen oxide (NO_x), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs) are emitted by waste activities, and are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 7-1 and Table 7-2.

Figure 7-1: 2001 Waste Chapter GHG Sources

Overall, in 2001, waste activities generated emissions of 246.6 Tg CO_2 Eq., or 3.6 percent of total U.S. greenhouse gas emissions.

Table 7-1: Emissions from Waste (Tg CO_2 Eq.)

Gas/Source	1990		1995	1996	1997	1998	1999	2000	2001
CH₄	**236.2**		**242.7**	**238.9**	**234.8**	**230.1**	**231.9**	**234.1**	**231.3**
Landfills	212.1		216.1	212.1	207.5	202.4	203.7	205.8	202.9
Wastewater Treatment	24.1		26.6	26.8	27.3	27.7	28.2	28.3	28.3
N₂O	**12.7**		**13.9**	**14.1**	**14.4**	**14.6**	**15.1**	**15.1**	**15.3**
Human Sewage	12.7		13.9	14.1	14.4	14.6	15.1	15.1	15.3
Total	**248.9**		**256.6**	**253.1**	**249.2**	**244.7**	**247.0**	**249.2**	**246.6**

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from Waste (Gg)

Gas/Source	1990		1995	1996	1997	1998	1999	2000	2001
CH₄	11,245		11,557	11,378	11,182	10,957	11,042	11,146	11,013
Landfills	10,099		10,290	10,100	9,880	9,639	9,701	9,798	9,663
Wastewater Treatment	1,147		1,267	1,278	1,301	1,318	1,341	1,348	1,350
N₂O	41		45	46	46	47	49	49	49
Human Sewage	41		45	46	46	47	49	49	49

Note: Totals may not sum due to independent rounding.

Landfills

Landfills are the largest anthropogenic source of CH_4 emissions in the United States. In 2001, landfill CH_4 emissions were approximately 202.9 Tg CO_2 Eq. (9,663 Gg). Emissions from municipal solid waste (MSW) landfills, which received about 61 percent of the total solid waste generated in the United States, accounted for about 94 percent of total landfill emissions, while industrial landfills accounted for the remainder. Over 2,100 operational landfills exist in the United States *(BioCycle* 2001), with the largest landfills receiving most of the waste and generating the majority of the CH_4.

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[1] Landfills also store carbon, due to incomplete degradation of organic materials such as wood products and yard trimmings, as described in the Land-Use Change and Forestry chapter.

After being placed in a landfill, biogenic waste (such as paper, food scraps, and yard trimmings) is initially digested by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which can break down organic matter into substances such as cellulose, amino acids, and sugars. These substances are further broken down through fermentation into gases, and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. Methane-producing anaerobic bacteria convert these fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent carbon dioxide (CO_2) and 50 percent CH_4, by volume.[2] Significant CH_4 production typically begins one or two years after waste disposal in a landfill and may last from 10 to 60 years.

[Begin Text Box]

Box 7-1: Biogenic Emissions and Sinks of Carbon

For many countries, CO_2 emissions from the combustion or degradation of biogenic materials are important because of the significant amount of energy they derive from biomass (e.g., burning fuelwood). The fate of biogenic materials is also important when evaluating waste management emissions (e.g., the decomposition of paper). The carbon contained in paper was originally stored in trees during photosynthesis. Under natural conditions, this material would eventually degrade and cycle back to the atmosphere as CO_2. The quantity of carbon that these degradation processes cycle through the Earth's atmosphere, waters, soils, and biota is much greater than the quantity added by anthropogenic greenhouse gas sources. But the focus of the United Nations Framework Convention on Climate Change is on anthropogenic emissions—emissions resulting from human activities and subject to human control—because it is these emissions that have the potential to alter the climate by disrupting the natural balances in carbon's biogeochemical cycle, and enhancing the atmosphere's natural greenhouse effect.

Carbon dioxide emissions from biogenic materials (e.g., paper, wood products, and yard trimmings) grown on a sustainable basis are considered to mimic the closed loop of the natural carbon cycle—that is, they return to the atmosphere CO_2 that was originally removed by photosynthesis. However, CH_4 emissions from landfilled waste occur due to the man-made anaerobic conditions conducive to CH_4 formation that exist in landfills, and are consequently included in this Inventory.

The removal of carbon from the natural cycling of carbon between the atmosphere and biogenic materials—which occurs when wastes of biogenic origin are deposited in landfills—sequesters carbon. When wastes of sustainable, biogenic origin are landfilled, and do not completely decompose, the carbon that remains is effectively removed from the global carbon cycle. Landfilling of forest products and yard trimmings results in long-term storage of about 153 Tg CO_2 Eq. and 5 to 18 Tg CO_2 Eq. per year, respectively. Carbon storage that results from forest products and yard trimmings disposed in landfills is accounted for in the Land-Use Change and Forestry chapter, as recommended in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) regarding the tracking of carbon flows.

[End Box]

From 1990 to 2001, net CH_4 emissions from landfills decreased by approximately 4 percent (see Table 7-3 and Table 7-4), with small increases occurring in some interim years. This slightly downward trend in overall emissions is the result of increases in the amount of landfill gas collected and combusted by landfill operators, which has more than offset the additional CH_4 emissions resulting from increases in the amount of MSW landfilled.

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[2] The percentage of CO_2 in biogas released from a landfill may be smaller because some CO_2 dissolves in landfill water (Bingemer and Crutzen 1987). Additionally, less than 1 percent of landfill gas is composed of non-methane volatile organic compounds (NMVOCs).

Methane emissions from landfills are a function of several factors, including: (1) the total amount of MSW in landfills, which is related to total MSW landfilled annually for the last 30 years; (2) the characteristics of landfills receiving waste (i.e., composition of waste-in-place; size, climate); (3) the amount of CH_4 that is recovered and either flared or used for energy purposes; and (4) the amount of methane oxidized in landfills instead of being released into the atmosphere. The estimated total quantity of waste-in-place contributing to emissions increased from about 4,926 Tg in 1990 to 6,280 Tg in 2001, an increase of 28 percent (see Annex O). During this period, the estimated CH_4 recovered and flared from landfills increased as well. In 1990, for example, approximately 1,190 Gg of CH_4 were recovered and combusted (i.e., used for energy or flared) from landfills. In 2001, the estimated quantity of CH_4 recovered and combusted increased to 5,263 Gg.

Over the next several years, the total amount of MSW generated is expected to increase slightly. The percentage of waste landfilled, however, may decline due to increased recycling and composting practices. In addition, the quantity of CH_4 that is recovered and either flared or used for energy purposes is expected to increase, as a result of a 1996 regulation that requires large MSW landfills to collect and combust landfill gas (see 40 CFR Part 60, Subparts Cc 2002), and an EPA program that encourages voluntary CH_4 recovery and use at landfills not affected by the regulation.

Table 7-3: CH_4 Emissions from Landfills (Tg CO_2 Eq.)

Activity	1990		1995	1996	1997	1998	1999	2000	2001
MSW Landfills	243.6		278.0	283.9	289.8	295.0	302.1	307.8	314.0
Industrial Landfills	17.1		19.5	19.9	20.3	20.6	21.1	21.5	22.0
Recovered									
Gas-to-Energy	(15.4)		(22.3)	(25.6)	(30.5)	(36.8)	(42.0)	(45.9)	(50.3)
Flared	(9.6)		(35.0)	(42.5)	(49.1)	(53.9)	(54.8)	(54.8)	(60.2)
Oxidized[1]	(23.6)		(24.0)	(24.2)	(24.2)	(24.1)	(23.7)	(23.2)	(22.6)
Total	212.1		216.1	212.1	207.5	202.4	203.7	205.8	202.9

Note: Totals may not sum due to independent rounding.
[1] Includes oxidation at both municipal and industrial landfills.

Table 7-4: CH_4 Emissions from Landfills (Gg)

Activity	1990		1995	1996	1997	1998	1999	2000	2001
MSW Landfills	11,559		13,238	13,520	13,802	14,047	14,385	14,659	14,954
Industrial Landfills	812		927	946	966	983	1,007	1,026	1,047
Recovered									
Gas-to-Energy	(732)		(1,064)	(1,220)	(1,452)	(1,752)	(2,002)	(2,187)	(2,396)
Flared	(458)		(1,668)	(2,024)	(2,338)	(2,568)	(2,611)	(2,611)	(2,867)
Oxidized[1]	(1,122)		(1,143)	(1,154)	(1,155)	(1,149)	(1,128)	(1,104)	(1,077)
Total	10,099		10,290	10,100	9,880	9,639	9,701	9,798	9,663

Note: Totals may not sum due to independent rounding.
[1] Includes oxidation at municipal and industrial landfills.

Methodology

Methane emissions from landfills were estimated to equal the CH_4 produced from municipal landfills, minus the CH_4 recovered and combusted, plus the CH_4 produced by industrial landfills, minus the CH_4 oxidized before being released into the atmosphere.

The methodology for estimating CH_4 emissions from municipal landfills is based on a model that updates the population of U.S. landfills each year. This model is based on the pattern of actual waste disposal, as evidenced in an extensive landfill survey by the EPA's Office of Solid Waste in 1986. A second model was employed to estimate emissions from the landfill population (EPA 1993). For each landfill in the data set, the amount of waste-in-place contributing to CH_4 generation was estimated using its year of opening, its waste acceptance rate, year of closure, and design capacity. Data on national municipal waste landfilled each year was apportioned by landfill.

Emissions from municipal landfills were then estimated by multiplying the quantity of waste contributing to emissions by emission factors (EPA 1993). For further information see Annex O.

The estimated landfill gas recovered per year was based on updated data collected from vendors of flaring equipment and a database of landfill gas-to-energy (LFGTE) projects compiled by EPA's Landfill Methane Outreach Program (LMOP). Based on the information provided by vendors, the CH_4 combusted by 642 flares in operation from 1990 to 2001 was estimated. This quantity likely underestimates flaring, because EPA does not have information on all flares in operation. Additionally, the LFGTE database provided data on landfill gas flow and energy generation for 334 operational LFGTE projects. If both flare data and LFGTE recovery data for a particular landfill were available, then the emissions recovery was based on the LFGTE data, which provides actual landfill-specific data on gas flow for direct use projects and project capacity (i.e., megawatts) for electricity projects. The flare data, on the other hand, only provided a range of landfill gas flow for a given flare size. Given that each LFGTE project was likely to also have had a flare, double counting reductions from flares and LFGTE projects was avoided by subtracting emissions reductions associated with LFGTE projects for which a flare had not been identified from the emissions reductions associated with flares.[3]

Emissions from industrial landfills were assumed to be equal to seven percent of the total CH_4 emissions from municipal landfills (EPA 1993). The amount of CH_4 oxidized by the landfill cover at both municipal and industrial landfills was assumed to be ten percent of the CH_4 generated that is not recovered (Liptay et al. 1998). To calculate net CH_4 emissions, both CH_4 recovered and CH_4 oxidized were subtracted from CH_4 generated at municipal and industrial landfills.

Data Sources

The landfill population model, including actual waste disposal data from individual landfills, was developed from a survey performed by the EPA's Office of Solid Waste (EPA 1988). National landfill waste generation and disposal data for 1991 through 2001 were obtained from *BioCycle* (2001). Because *BioCycle* does not account for waste generated in U.S. territories, waste generation for the territories was estimated using population data obtained from the U.S. Census Bureau (2000) and per capita MSW generation from EPA's *Municipal Solid Waste Disposal in the United States* report (2002a). Documentation on the landfill CH_4 emissions methodology employed is available in EPA's *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress* (EPA 1993). Information on flares was obtained from vendors (ICF 2002), and information on landfill gas-to-energy projects was obtained from the EPA's Landfill Methane Outreach Program database (EPA 2002a).

Uncertainty

Several types of uncertainty are associated with the estimates of CH_4 emissions from landfills. The primary uncertainty concerns the characterization of landfills. Information is not available for waste in place for every landfill - a fundamental factor that affects CH_4 production. The heterogeneity of waste disposed in landfills is uncertain as well. The approach used here assumes that the landfill set is representative of waste composition and reflects this heterogeneity. Also, the approach used to estimate the contribution of industrial non-hazardous wastes to total CH_4 generation employs introduces uncertainty. Aside from uncertainty in estimating CH_4 generation potential, uncertainty exists in the estimates of oxidation efficiency. Overall, uncertainty in the landfill CH_4 emission rate is estimated to be roughly ±30 percent.

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[3] Due to the differences in referencing landfills and incomplete data on the national population of flares, matching flare vendor data with the LFGTE data was problematic and a flare could not be identified for each of the LFGTE projects. Because each LFGTE project likely has a flare, the aggregate estimate of emission reductions through flaring was reduced by the LFGTE projects for which a specific flare could not be identified. This approach eliminated the potential for double counting emissions reductions at landfills with both flares and a LFGTE project.

The N_2O emissions from application of sewage sludge on landfills are not explicitly modeled as part of greenhouse gas emissions from landfills. Nitrous oxide emissions from sewage sludge applied to landfills would be relatively small because the microbial environment in landfills is not very conducive to the nitrification and denitrification processes that result in N_2O emissions. The total nitrogen (N) in sewage sludge increased from 178 to 234 Gg total N between 1990 and 2001. The quantity of sewage sludge applied to landfills decreased from 28 to 11 percent from 1990 to 2001.

Wastewater Treatment

Wastewater from domestic sources (municipal sewage) and industrial sources is treated to remove soluble organic matter, suspended solids, pathogenic organisms, and chemical contaminants. Treatment may either occur off-site or on-site. For example, in the United States, approximately 25 percent of domestic wastewater is treated in septic systems or other on-site systems. Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. The resulting biomass (sludge) is removed from the effluent prior to discharge to the receiving stream. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces CH_4. During collection and treatment, wastewater may be accidentally or deliberately managed under anaerobic conditions. In addition, the sludge may be further biodegraded under aerobic or anaerobic conditions. Untreated wastewater may also produce CH_4 if contained under anaerobic conditions.

The organic content, expressed in terms of either biochemical oxygen demand (BOD) or chemical oxygen demand (COD), determines the CH_4 producing potential of wastewater. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes. COD refers to the amount of oxygen consumed under specified conditions in the oxidation of the organic and oxidizable inorganic matter and is a parameter typically used to characterize industrial wastewater. Under anaerobic conditions and with all other parameters, such as temperature, being the same, wastewater with higher organic content will produce more CH_4 than wastewater with lower BOD or COD.

In 2001, CH_4 emissions from domestic wastewater treatment were 13.9 Tg CO_2 Eq. (660 Gg). Emissions have increased since 1990 in response to the increase in the U.S. human population. Industrial emission sources include wastewater from the following industries: pulp and paper; meat and poultry processing; and vegetables, fruits and juices processing.[4] In 2001, CH_4 emissions from industrial wastewater treatment were 14.5 Tg CO_2 Eq. (690 Gg). Table 7-5 and Table 7-6 provide emission estimates from domestic and industrial wastewater treatment.

Table 7-5: CH_4 Emissions from Domestic and Industrial Wastewater Treatment (Tg CO_2 Eq.)

Activity	1990		1995	1996	1997	1998	1999	2000	2001
Domestic	12.1		12.9	13.0	13.2	13.4	13.5	13.7	13.9
Industrial*	12.0		13.7	13.8	14.2	14.3	14.6	14.6	14.5
Total	**24.1**		**26.6**	**26.8**	**27.3**	**27.7**	**28.2**	**28.3**	**28.3**

* Industrial activity includes the following industries: pulp and paper; meat and poultry; and vegetables, fruits and juices processing.
Note: Totals may not sum due to independent rounding.

Table 7-6: CH_4 Emissions from Domestic and Industrial Wastewater Treatment (Gg)

Activity	1990		1995	1996	1997	1998	1999	2000	2001
Domestic	576		613	620	627	637	644	651	660
Industrial*	571		653	658	674	681	697	697	690
Total	**1147**		**1267**	**1278**	**1301**	**1318**	**1341**	**1348**	**1350**

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[4] Industrial wastewater emissions from petroleum systems are included in the petroleum systems section in the Energy chapter.

Methodology

Domestic wastewater CH_4 emissions were estimated using the default IPCC methodology (IPCC 2000). The total population for each year was multiplied by a per capita wastewater BOD production rate to determine total wastewater BOD produced. It was assumed that 0.065 kilograms of wastewater BOD_5[5] was produced per day per capita and that 16.25 percent of wastewater BOD_5 was anaerobically digested. This proportion of BOD was then multiplied by an emission factor of 0.6 kg CH_4/kg BOD_5.

A top-down approach was used to develop estimates of CH_4 emissions from industrial wastewater according to the methodology described in the IPCC *Good Practice Guidance* (IPCC 2000). Industry categories were identified that are likely to have significant CH_4 emissions from their wastewater treatment. Industries were chosen that typically have both a high volume of wastewater generated and a high organic COD wastewater load. The top three industries that met these criteria were:

- Pulp and paper manufacturing
- Meat and poultry packing
- Vegetables, fruits and juices processing

Methane emissions from these categories were estimated by multiplying the annual product output (metric tons/year) by the average outflow (m^3/ton of output), the organics loading in the outflow (grams of organic COD/m^3), the emission factor (grams CH_4/grams COD), and the percentage of organic COD assumed to degrade anaerobically.

Wastewater treatment for the pulp and paper industry typically includes neutralization, screening, sedimentation, and flotation/hydrocycloning to remove solids (World Bank 1999, Nemerow 1991). The most important step is lagooning for storage, settling, and biological treatment (secondary treatment). In developing estimates for this category, BOD was used instead of COD, because more accurate BOD numbers were available. In determining the percent that degraded anaerobically, both primary and secondary treatment were considered. Primary treatment lagoons are aerated to reduce anaerobic activity. However, the lagoons are large and zones of anaerobic activity may occur. Approximately 42 percent of the BOD passes on to secondary treatment, which are less likely to be aerated (EPA 1993). It was assumed that 25 percent of the BOD in secondary treatment lagoons degrades anaerobically, while 10 percent passes through to be discharged with the effluent (EPA 1997a). Overall, the percentage of wastewater organics that degrade anaerobically was determined to be 10.3 percent. The emission factor that was used is 0.6 kg CH_4/kg BOD, which is the default emission factor from IPCC (2000).

The meat and poultry processing industry makes extensive use of anaerobic lagoons, and it was estimated that 77 percent of all wastewater organics from this industry degrades anaerobically (EPA 1997b).

Treatment of wastewater from fruits, vegetables, and juices processing includes screening, coagulation/settling and biological treatment (lagooning). The flows are frequently seasonal, and robust treatment systems are preferred for on-site treatment. Effluent is suitable for discharge to the sewer. Therefore, it was assumed that this industry is likely to use lagoons intended for aerobic operation, but that the large seasonal loadings may develop limited anaerobic zones. In addition, some anaerobic lagoons may also be used. Consequently, it was estimated that 5 percent of these wastewater organics degrade anaerobically.

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[5] The 5-day biochemical oxygen demand (BOD) measurement (Metcalf and Eddy 1991).

Data Sources

National population data for 1990 to 2001 used in the domestic wastewater emissions estimates, were based on data from the U.S. Census Bureau (2001). Per-capita production of BOD_5 for domestic wastewater was obtained from the EPA (1997b). The emission factor (0.6 kg CH_4/kg BOD_5) employed for domestic wastewater treatment was taken from IPCC (2000). The same emission factor was used for pulp and paper wastewater, whereas the emission factor for meat and poultry, and vegetables, fruits and juices category is 0.25 kg CH_4/kg COD (IPCC 2000).

Table 7-7 provides U.S. population and wastewater BOD data.

Table 7-7: U.S. Population (Millions) and Wastewater BOD Produced (Gg)

Year	Population	BOD_5
1990	249	5,905
1991	252	5,983
1992	255	6,054
1993	257	6,102
1994	261	6,196
1995	265	6,291
1996	268	6,363
1997	271	6,434
1998	275	6,529
1999	278	6,600
2000	281	6,681
2001	285	6,766

For pulp and paper, a time series of CH_4 emissions for post-1990 years was developed based on production figures reported in the Lockwood-Post Directory (Lockwood-Post Directory 1992 - 2002). The overall wastewater outflow was estimated to be 85 m^3/ton and the average BOD loading entering the secondary treatment lagoons was estimated to be 0.4 gram BOD/liter. Both values are based on information from multiple handbooks.

Production data for the meat and poultry industry were obtained from the U.S. Census (2001). EPA (1997b) provides wastewater outflows of 13 (out of a range of 8 to 18) m^3/ton and an average COD value of 4.1 (out of a range of 2 to 7) g/liter. These parameters are currently undergoing review, based on a recent comprehensive survey conducted by EPA's Office of Water (EPA, 2002).

The USDA National Agricultural Statistics Service (USDA 2001) provided production data for the fruits, vegetables, and juices processing sector. Outflow data for various subsectors (canned fruit, canned vegetables, frozen vegetables, fruit juices, jams, baby food) were obtained from World Bank (1999) and an average wastewater outflow of 5.6 m^3/ton was used. For the organics loading, a COD value of 5 (out of a range of 2 to 10) g/liter was used (EPA 1997b).

Table 7-8 provides U.S. pulp and paper; meat and poultry; and vegetables, fruits, and juices production data.

Table 7-8: U.S. Pulp and Paper, Meat and Poultry, and Vegetables, Fruits and Juices Production (Million Metric Tons).

Year	Pulp and paper	Meat and Poultry	Vegetables, Fruits and Juices
1990	128.9	28.2	29.7
1991	129.2	29.0	30.8
1992	134.5	30.0	32.9
1993	134.1	31.0	33.6
1994	139.3	32.0	36.7
1995	140.9	33.6	36.2
1996	140.3	34.2	35.9

1997	145.6	34.6	37.1
1998	144.0	35.7	35.9
1999	145.1	37.0	36.8
2000	142.8	37.4	38.3
2001	134.3	38.6	34.3

Uncertainty

Domestic wastewater emissions estimates are uncertain due to the lack of data on the occurrence of anaerobic conditions in treatment systems, especially incidental occurrences.

Large uncertainties are associated with the industrial wastewater emission estimates. Wastewater outflows and organics loading may vary greatly for different plants and different sub-sectors (e.g. paper vs. board, poultry vs. beef, baby food vs. juices, etc.). Also, the degree to which anaerobic degradation occurs in treatment systems is very difficult to assess. In addition, it is believed that pulp and paper, meat and poultry and vegetables, fruits and juices are the most significant industrial sources, but there may be additional sources that also produce wastewater organics that may degrade under anaerobic conditions (e.g., organic chemicals and plastics production).

Human Sewage (Domestic Wastewater)

Domestic human sewage is usually mixed with other household wastewater, which includes shower drains, sink drains, washing machine effluent, etc., and transported by a collection system to either a direct discharge, an on-site or decentralized wastewater treatment (WWT) system, or a centralized WWT system. Decentralized WWT systems are septic systems and package plants. Centralized WWT systems may include a variety of processes, ranging from lagooning to advanced tertiary treatment technology for removing nutrients. Often, centralized WWT systems also treat certain flows of industrial, commercial, and institutional wastewater. After processing, treated effluent may be discharged to a receiving water environment (e.g., river, lake, estuary, etc.), applied to soils, or disposed of below the Earth's surface.

Nitrous oxide may be generated during both nitrification and denitrification of the nitrogen present, usually in the form of urea, ammonia, and proteins. These are converted to nitrate via nitrification, an aerobic process converting ammonia-nitrogen into nitrate (NO_3^-). Denitrification occurs under anoxic conditions (without free oxygen), and involves the biological conversion of nitrate into dinitrogen gas (N_2). Nitrous oxide can be an intermediate product of both processes, but is more often associated with denitrification.

The U.S. quantifies two distinct sources for N_2O emissions from domestic wastewater: emissions from wastewater treatment (WWT) processes, and emissions from effluent that has been discharged into aquatic environments. The 2001 emissions of N_2O from WWT processes and from effluent were estimated to be 0.3 Tg CO_2 Eq. (0.9 Gg) and 15.0 Tg CO_2 Eq. (48.5 Gg), respectively. Total N_2O emissions from domestic wastewater were estimated to be 15.3 Tg CO_2 Eq. (49.3 Gg). (See Table 7-9).

Table 7-9: N_2O Emissions from Human Sewage

Year	Tg CO_2 Eq.	Gg
1990	12.7	41
1995	13.9	45
1996	14.1	46
1997	14.4	46
1998	14.6	47
1999	15.1	49
2000	15.1	49
2001	15.3	49

Methodology

Nitrous oxide emissions from human sewage effluent disposal were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997) with three modifications (see below). The IPCC method assumes that nitrogen disposal—and thus N_2O emissions associated with land disposal, subsurface disposal, as well as domestic WWT— are negligible and that all nitrogen is discharged directly into aquatic environments.

- In the United States, some nitrogen is removed with the sewage sludge, which is land applied, incinerated or landfilled. The nitrogen disposal into aquatic environments is thus reduced to account for the sewage sludge application.

- Emissions from wastewater treatment plants (WWTPs) are not accounted for in the current IPCC methodology. A new overall emission factor of 4 g N_2O/person.year is used to estimate N_2O emissions from U.S. municipal WWTPs. This emission factor is based on a factor of 3.2 g N_2O/person-year (Czepiel, 1995) multiplied by 1.25 to adjust for co-discharged industrial nitrogen. The nitrogen quantity associated with these emissions is calculated by multiplying the N_2O emitted by $^{(2 \times 14)}/_{44}$.

- The IPCC method uses annual, per capita protein consumption (kg/year). This number is likely to underestimate the amount of protein entering the sewer or septic system. Food (waste) that is not consumed is often washed down the drain, as a result of the use of garbage disposals. Also, bath and laundry water can be expected to contribute to nitrogen loadings. Furthermore, industrial wastewater co-discharged with domestic wastewater is not accounted for in the existing methodology. A factor of 1.75 is applied to protein consumption to account for the extra nitrogen from these sources.

With the modifications described above, N_2O emissions from domestic wastewater were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997). This methodology is illustrated below:

$$N_2O(s) = (US_{POP} \times 0.75 \times EF_1) + \{[(Protein \times 1.75 \times Frac_{NPR} \times US_{POP}) - N_{WWT} - N_{sludge}] \times EF_2 \times {^{44}/_{28}}\}$$

where,
   $N_2O(s)$ = N_2O emissions from domestic wastewater ("human sewage")
   US_{POP} = U.S. population
   0.75 = Fraction of population using WWTPs (as opposed to septic systems)
   EF_1 = Emission factor (4 g N_2O/person.year)
   Protein = Annual, per capita protein consumption
   1.75 = Fraction of non-consumption protein in domestic wastewater
   $Frac_{NPR}$ = Fraction of nitrogen in protein
   N_{WWT} = Quantity of wastewater nitrogen removed by WWT processes $[(US_{POP} \times 0.75 \times EF_1) \times {^{28}/_{44}}]$
   N_{sludge} = Quantity of sewage sludge N not entering aquatic environments
   EF_2 = Emission factor (kg N_2O-N/kg sewage-N produced)
   $(^{44}/_{28})$ = The molecular weight ratio of N_2O to N_2

Data Sources

U.S. population data were taken from the U.S. Census Bureau (2001). The fraction of the US population using WWTPs is from the NEEDS Survey (1996). The emission factor (EF_1) used to estimate emissions from WWT is based on Czepiel, et al. (1995). Data on annual per capita protein consumption were provided by the United Nations Food and Agriculture Organization (FAO 2001) (See Table 7-10). Because data on protein intake were unavailable for 2001, the value of per capita protein consumption for the previous year was used. The fraction of non-consumption protein in domestic wastewater is based on expert judgment and on Metcalf & Eddy (1991) and Mullick (1987). An emission factor to estimate emissions from effluent (EF_2) has not been specifically estimated for the United States, so the default IPCC value (0.01 kg N_2O-N/kg sewage-N produced) was applied. The fraction of nitrogen in protein (0.16 kg N/kg protein) was also obtained from IPCC/UNEP/OECD/IEA (1997).

Table 7-10: U.S. Population (Millions) and Average Protein Intake (kg/Person/Year)

Year	Population	Protein
1990	250	39.2
1991	253	39.8
1992	257	40.0
1993	260	40.2
1994	263	41.2
1995	266	40.6
1996	269	40.7
1997	273	41.0
1998	276	41.1
1999	279	41.9
2000	282	41.6
2001	285	41.6

Uncertainty

The U.S. population, per capita protein intake data (Protein), and fraction of nitrogen in protein ($Frac_{NPR}$) are believed to be fairly accurate. Large uncertainty exists, however, in the emission factor for effluent (EF_2). This uncertainty is due to regional differences in the receiving waters that would likely affect N_2O emissions but are not accounted for in the default IPCC factor. Also, the emission factor for emissions from WWT (EF_1) is uncertain. When more plants incorporate nitrification/denitrification in the future, this emission factor is likely to increase. However, emissions from WWT are less significant than emissions from effluent-surface water. Taken together, these uncertainties present significant difficulties in estimating N_2O emissions from domestic wastewater.

Waste Sources of Ambient Air Pollutants

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of criteria air pollutant emissions. Total emissions of NO_x, CO, and NMVOCs from waste sources for the years 1990 through 2001 are provided in Table 7-11.

Table 7-11: Emissions of NO_x, CO, and NMVOC from Waste (Gg)

Gas/Source	1990		1995	1996	1997	1998	1999	2000	2001
NO$_x$	+		**1**	**3**	**3**	**3**	**3**	**3**	**3**
Landfills	+		1	2	2	2	3	3	3
Wastewater Treatment	+		+	+	+	+	+	+	+
Miscellaneous[a]	+		1	1	1	1	+	+	+
CO	1		**2**	**5**	**5**	**5**	**14**	**14**	**14**
Landfills	1		2	5	5	5	13	13	13
Wastewater Treatment	+		+	+	+	+	1	1	1
Miscellaneous[a]	+		1	+	+	+	+	+	+
NMVOCs	673		**731**	**158**	**157**	**161**	**151**	**153**	**158**
Landfills	58		68	32	32	33	29	29	30
Wastewater Treatment	57		61	61	62	63	64	65	68
Miscellaneous[a]	558		602	65	64	65	58	59	60

[a] Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.
Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.5 Gg

Methodology and Data Sources

These emission estimates were taken directly from EPA data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2003). This EPA report provides emission estimates of these gases by sector, using a "top down" estimating procedure—emissions were calculated either for individual sources or for

many sources combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual source categories from various agencies. Depending on the source category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Activity data were used in conjunction with emission factors, which relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA data bases.

Uncertainty

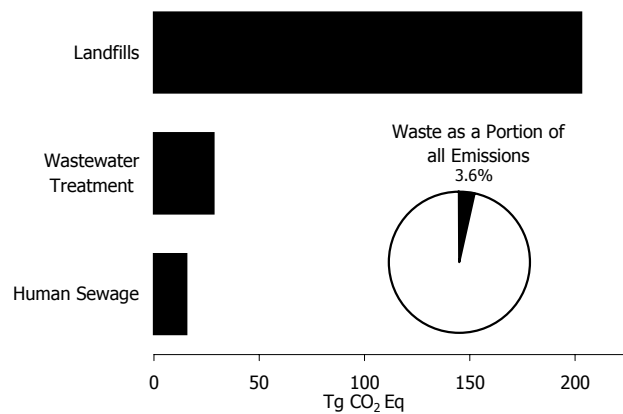Uncertainties in these estimates are primarily due to the accuracy of the emission factors used and accurate estimates of activity data.

Figure 7-1: 2001 Waste Chapter GHG Sources